Results of Recent Investigations of Jupiter's Decametric Radiation

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The activity of Jupiter's decametric radiation appears to be greatest between 5 and 10 Mc/s, but measurements made below 10 Mc/s are subject to large ionospheric errors. No significant change in rotation period has appeared since 1960. The effect of the satellite Io as reported by Bigg has been corroborated. Marked variations in axial ratio with System III longitude were observed, from which estimates were made of the meridians of the poles. A ray-tracing study was made of the focussing of radiation escaping from possible Jovian field-aligned ducts. The effect of asymmetrical stop zones is discussed. A possible explanation of the influence of Io is offered.

1. Introduction

Systematic observations of the decametric radiation from Jupiter have been conducted by the University of Florida group at Gainesville since 1956, and at the Maipu Radioastronomical Observatory in Chile since 1959. Monitored recordings are regularly made with simple calibrated radiometers at several fixed frequencies between 5 and 52 Mc/s. Intensities of the circular polarization components are measured at three of the frequencies. Recordings of the dynamic spectra and detailed structure of bursts are made during the more intense noise storms. The purpose of this paper is to present some of the more recent results of the observational program, and of related theoretical investigations.

2. Average Spectra

One of the objectives of the program has been the determination of the average spectral distribution of the decametric radiation occurring during an entire apparition. Such a spectrum is shown in Figure 1. In order to illustrate the relationship between the decameter-wavelength region and the other parts of Jupiter's radio spectrum, the decimeter-wavelength and thermal regions have also been included. Since the decameter radiation is highly sporadic, the curve for the peak flux densities lies considerably above that for the average.

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There is considerable uncertainty regarding the spectra below 10 Mc/s, due to the proximity of the ionospheric critical frequency. The smooth curves for the decameter region were obtained in 1961 [Carr et al., 1964]; points obtained more recently are also shown. The maximum activity as observed at ground level between midnight and dawn during the years of minimum sunspot number apparently occurs between 5 and 10 Mc/s. Whether or not future observations to be made from above the ionosphere will reveal that the true maximum lies at a significantly lower frequency than this remains to be seen.

Figure 2 suggests that the true maximum could indeed occur at a lower frequency. This figure is a scatter diagram of the peak flux densities of a series of Jupiter noise bursts at 6.3 Mc/s as a function of the F-region critical frequency for the ordinary mode in the terrestrial ionosphere. Jupiter was near the zenith at the times of observation, and the sunspot number was close to its minimum. The figure suggests that ionospheric attenuation of the 6.3 Mc/s signals was quite severe whenever the critical frequency exceeded the relatively low value of 2.5 Mc/s. It would therefore seem that flux density measurements from beneath the ionosphere at frequencies less than 10 Mc/s can serve only as lower limits, unless adequate correction can be made for attenuation.

3. Periodicities

Although the occurrence of the Jovian decameter radiation appears superficially to be random, statistical analyses have revealed three pronounced periodicities. These are (a) the System III rotation period, (b) the period of the satellite Io in its orbital motion about Jupiter, and (c) the 11-year period of the sunspot cycle.

Plots of the probability of occurrence of the radiation as a function of the System III longitude of the central meridian usually indicate three major source zones, as shown in Figure 8. The sources are easily recognizable at the higher frequencies. They grow wider as the frequency is reduced, and below about 15 Mc/s become poorly defined. Their positions appeared to remain fixed in terms of System III longitude until 1960. Since 1960, however, they have drifted toward higher longitudes at the rate of about 11° per year. The implication is that the rotation period of the radio sources increased rather abruptly by about one second in 1960, and has remained essentially constant since that time. These results have been presented in detail by Smith et al. [1965]. More recent results, through the 1964 apparition, indicate no further change in the rotation period.

A striking correlation of the Jovian decametric activity with the position of the satellite Io was discovered by Bigg [1964]. The recent re-examination of all the Florida and Chile data has resulted in the complete corroboration of Bigg's findings. These results, together with evidence for a similar but less pronounced influence by the satellites Gannymede and Europa, have been presented by Lebo et al. [1965].

It has long been known that an inverse correlation exists between the yearly averages of Jupiter activity and sunspot number. Recently obtained results from the 1964 apparition indicate a continued rise in Jupiter activity. The minimum in Jupiter activity lagged the sunspot maximum by about a year. It will be of interest to determine whether a similar lag exists between the Jupiter activity maximum and the sunspot minimum.

4. Polarization

Extensive measurements of the intensities of the right and left circular components of the Jupiter radiation have been made at the University of Florida and in Chile. Typical noise bursts are a second or so in duration. The apparent axial ratio, α, which is measured for each burst, is given by

$$\alpha = \frac{S_L^{\frac{1}{2}} - S_R^{\frac{1}{2}}}{S_L^{\frac{1}{2}} + S_R^{\frac{1}{2}}}$$

In this expression S_L and S_R are the flux densities of the left and right circular components of the burst peak, not including the contribution from the galactic background. The magnitude of the apparent axial ratio is less than or equal to that of the true axial ratio, being less if an unpolarized component is present. There is usually a fairly large random variation in the values of α for successive bursts; however, it has been found that smoothing can reveal significant variations.

Carr et al. [1961] demonstrated that at 22.2 Mc/s the algebraic averages of α for the three major source zones varied slightly but significantly. The right circular component was predominant for all three, but source C displayed the greatest tendency toward left-handedness. Dowden [1963] showed that there was a pronounced variation in the smoothed values of α with respect to longitude at 10 Mc/s, the polarization sense actually changing with longitude.

Figure 3 shows some results of observations at 22.2 Mc/s in Florida and in Chile during 1962 and 1963. The algebraic averages of α over 20° longitude intervals are plotted with respect to System III longitude. Although α definitely became positive in a region of low activity near 360°, this portion of each curve is rather poorly defined.

Figure 4 illustrates the same type of results for 15.8 Mc/s observations made in Chile during 1962 and 1963. It should be noted that these two curves are remarkably similar, except that the one for 1963 is displaced 10° to 20° toward higher longitudes relative to that for 1962. This displacement is presumably due to the slight error in the assumed rotation period.

Preliminary results at 10 Mc/s are presented in Figure 5. The curve in this case was obtained from the observations of only one month; it is nevertheless surprisingly regular.

An averaged curve for each of the three frequencies is shown in Figure 6, correction having been made for the yearly longitude drift. It is seen that the longitude zone in which the polarization sense is left-hand widens as the frequency is reduced, until at 10 Mc/s it is almost 180° wide.

Figure 7 shows the distribution of apparent axial ratio values of individual bursts at 10, 15.8, and 22.2 Mc/s. Although the most probable axial ratio values were about ±0.55 for 10 Mc/s and about -0.45 for the higher frequencies, the values ±1.0 occurred relatively often.

In several of the theories which have been suggested to account for the radiation, emission occurs in the extraordinary mode, at or near the local electron gyrofrequency. The magnetic field is assumed to be that of a dipole which is inclined about 10° with respect to the rotational axis and is offset from the center of the planet. Assuming that no reflections occur, that the extraordinary mode remains predominant, and that the early propagation is more or less along the field lines, certain generalizations can be made regarding the magnetic poles. One can conclude that the field-source and field-sink poles must lie near the longitudes at the centers of the regions of right-hand and left-hand polarization, respectively, in Figure 6. The System III longitude of the field-source pole in 1963 would thus have been about 215°, and that of the field-sink pole about 35°. Observations of the synchrotron radiation at decimeter wavelengths have indicated that the geographic north and south poles are at System III longitudes of about 200° and 20°, respectively.

The highest frequency at which the decametric radiation has been obtained is about 40 Mc/s. It is clear from Figure 6 that any radiation occurring at 40 Mc/s must have been polarized in the right-hand sense. We can thus conclude that the surface value of the magnetic field intensity at the field-source pole is at least 14 gauss. On the other hand, Figure 6 suggests that the cut-off frequency for the left circular component is not far from 28 Mc/s, indicating that the field at the sink pole is at least 10 gauss. The magnetic dipole must therefore be displaced from the center of the planet toward the field-source pole, as was also concluded by Dowden [1963].

Figure 8 shows the relationship between the longitude distributions of occurrence probability and apparent axial ratio. The assumed longitudes of the source and sink poles are indicated. The meridian of the field-source pole passes between radiation sources A and B. Source C seems to lie largely in the opposite hemisphere, but its center does not occur very close to the meridian of the field-sink pole.

Polarization measurements of the radiation from Jupiter at 6.3 Mc/s were made in 1964 from a deep valley near the Arecibo Ionospheric Observatory in Puerto Rico. Despite the shielding afforded by the valley walls, and the prevailing near-optimum conditions for propagation through the ionosphere, most of the recordings were unusable because of excessive atmospheric noise from local thunderstorms. Nevertheless, some interesting effects were observed. On one occasion, an unusually long Jupiter noise storm persisted from before dawn until after sunrise. At the start, the right circular component was stronger than the left. However, as the critical frequency increased, the right circular component grew progressively weaker relative to the left circular component, as shown in Figure 9. The effect was presumably caused by the selective absorption of the right circular (extraordinary) component as the ionization increased. This bears out the earlier conclusion that results of observations at the lower frequencies are likely to be misleading if corrections for ionospheric effects are not made.

Another interesting observation made at Arecibo was that the noise bursts apparently lengthen when the frequency is lowered sufficiently. The durations of most of the bursts at 6.3 Mc/s ranged from about 10 to 100 seconds, while at 10 Mc/s or higher, the majority are between 1 and 10 seconds in length.

5. Theoretical Studies of Propagation in the Jovian Magnetosphere

Carr [1962] has suggested that field-aligned layers of slightly enhanced ionization in Jupiter's magnetosphere may strongly influence the propagation of the radiation produced at high latitudes. Rays which were initially trapped beneath a layer would escape from the duct when the transverse electron density gradient became insufficient to bend the ray along the field line. A partial focussing would occur upon escape, and rays of different frequencies would escape in slightly different directions. This effect, combined with the rotation of the planet and assumed departures of the field configuration from that of a symmetrically oriented dipole, could account qualitatively for several of the observed phenomena.

Gulkis [1965] recently carried out a quantitative investigation of the focussing of the radiation escaping from a field-aligned duct. He used a ray-tracing procedure patterned after that employed by Yabroff [1961] for whistler studies. A dipole field with its axis tipped 10°, and a magnetosphere containing a duct having a gaussian profile were assumed. Ray tracings were made for each of many combinations of frequency, initial wave normal direction, ambient electron density distribution, magnetic field intensity, and the strength, thickness, and location of the duct. Duct enhancement factors as low as 20 or 30 percent were found to be effective. Focussing occurred for certain seemingly plausible combinations of the adjustable parameters. A change in frequency of more than 1 or 2 Mc/s was necessary in order to change the direction of the focussed rays appreciably; it appears significant that this is the approximate bandwidth of the observed noise bursts. Calculations indicated that the presence of the duct increased the intensity of the radiation in the direction of focussing by about 12 decibels above what it would have been without the duct.

As expected, it was found that as either of the poles approached the central meridian, the frequency of the radiation focussed toward the earth drifted to higher values. After the pole crossed the central meridian the direction of frequency drift reversed. The calculated rate of frequency drift was of the same order of magnitude as the observed values. Since only the extraordinary mode was assumed to be present initially, waves of opposite senses of elliptical polarization would originate from opposite sides of the magnetic equator. It was concluded that the field-aligned duct model could readily be adjusted to predict several of the observed phenomena on a semi-quantitative basis.

Radiation generated in a planetary magnetosphere in the extraordinary mode at or below the local electron gyrofrequency normally cannot escape. It is confronted by a stop zone, i.e., a region in which the refractive index is imaginary [Booker, 1962]. For propagation along a field line, the inner stop zone boundary occurs where the gyrofrequency equals the wave frequency. The thickness of the stop zone depends upon both the magnetic field and the electron density; the thickness would decrease if the electron density were decreased or if the magnetic field were increased. The doppler-shifted gyro-radiation in the Ellis-McCulloch [1963] theory can escape provided the shift is to a high enough frequency. In such a case, the region in which the radiation is emitted lies outside the outer stop-zone boundary.

In two of the other emission models which have been proposed, the radiation has been assumed to result from the Cerenkov process and from amplified whistlers, respectively. The stop zone would prevent escape in either case, according to the usual magnetoionic theory. However, Piddington [1960] refers to possible ways in which radiation emitted in the extraordinary mode might penetrate the stop zone in the case of solar radiation. In these processes, the extraordinary waves are assumed to create ordinary waves at the stop zone, and the latter readily escape. If this is indeed taking place in Jupiter's magnetosphere, then our earlier conclusions regarding the types of poles at the two specified longitudes are incorrect. Thus the pole at 215° longitude would be the field-sink rather than the field-source pole.

Gulkis [1965] has pointed out that for all three models, i.e., doppler-shifted cyclotron emission, Cerenkov emission, and escaped whistlers, a decrease in the stop zone thickness would increase the probability of emission. An asymmetrical dipole field could thus give rise to an asymmetrical distribution of the radiation with respect to longitude. This effect might account in large part for the observed variation of occurrence probability with longitude. It is perhaps significant that the dipole center, as determined from the measurements of Berge and Morris [1964] at decimeter wavelengths, is closest to the surface of the planet at the longitude of source B. The stronger field at this longitude would result in a reduction in the stop-zone thickness, with a concomitant increase in emission probability. The other sources might then be explained on the basis of localized field distortions, causing either thinner stop zones, or field-aligned duct orientations more favorable for escape toward the earth, or both.

The remarkable influence of the satellite Io in triggering the radiation from Jupiter may well provide the key leading to the solution of the mystery of the origin of the decameter radiation. In one of the two configurations of maximum emission probability, source B is on the central meridian and the orbital position angle of Io, relative to superior geocentric conjunction is about 90° (Bigg, 1965; Lebo et al., 1965). In the other favorable configuration, source A is on the central meridian and the position angle of Io is about 240°. Io is thus close to the position of maximum elongation in both cases. It is conceivable, although not very likely, that the phenomenon results from magnetospheric tides raised by Io. One would expect two diametrically opposite tidal crests. As each of the troughs between the crests crosses the central meridian, the accompanying decrease in the thickness of the stop zone might allow radiation to escape toward the earth.

We suggest another explanation which is perhaps more plausible. Io travels among the charged particles trapped in Jupiter's Van Allen Belts. We assume that it has acquired an ionosphere of its own, particularly on its windward side. This ionosphere must be highly diamagnetic. The field lines in Jupiter's rotating magnetosphere would thus spread apart as they slip past Io, converging to their original positions on the other side. Trapped particles following the bulging field lines would be kept well outside Io's ionosphere, and would not collide with it. However, perturbation of the field near Io might somehow precipitate trapped electrons into the ionosphere. One such possibility is that the changing field would accelerate certain electrons and would decelerate others; the lowered mirroring altitude of those accelerated could result in their precipitation.

There might thus be a continual dumping of particles which had been trapped along those field lines passing closest to Io. As Warwick has suggested [1963], the dumping of previously trapped particles into Jupiter's ionosphere might result in the emission of Cerenkov radiation. In Warwick's original model, Cerenkov radiation from dumped electrons is reflected from the top of the ionosphere back toward the earth. However, we will assume that the radiation merely grazes the top of the ionosphere. The various rays from a point source in the region of dumping are refracted to a greater or less extent away from the planet, leaving a zone of shadow beneath a sharply defined ray envelope. This bounding surface approaches a wide-angle cone at some distance from the planet. The angular width of the cone is only slightly less than 180°. The rays closest to it are essentially parallel. The layer of parallel rays sweeps past the earth when Io is near either of the two positions of maximum elongation, resulting in the observed increases in activity. The observed radiation would come from regions near Jupiter's limb rather than from the so called "sources" on the central meridian.

It is not clear why such radiation should not be observed every time Io is near maximum elongation. The explanation is very likely closely related to the geometrical effects of dipole tilt, dipole eccentricity, and distortion of the field from that of a true dipole. It seems significant in this connection that for both of the configurations resulting in maximum emission, the pole near 200° longitude lies between the meridian of Io and the central meridian. Such mirror-image symmetry between the two configurations suggests a simple geometrical explanation based on a tilted dipole. However, it would undoubtedly be complicated by other factors such as stop-zone assymmetries and propagation anisotropy.

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6. References

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Figure Captions

Figure 1. Spectral distribution of Jupiter's radio emission. The decameter-wavelength curves are for 1961.

Figure 2. Effect of critical frequency upon flux density of noise bursts.

Figure 3. Variation of polarization with longitude at 22.2 Mc/s. Bar heights indicate standard deviation for a single measurement.

Figure 4. Variation of polarization with longitude at 15.8 Mc/s. Bar heights indicate standard deviation for a single measurement.

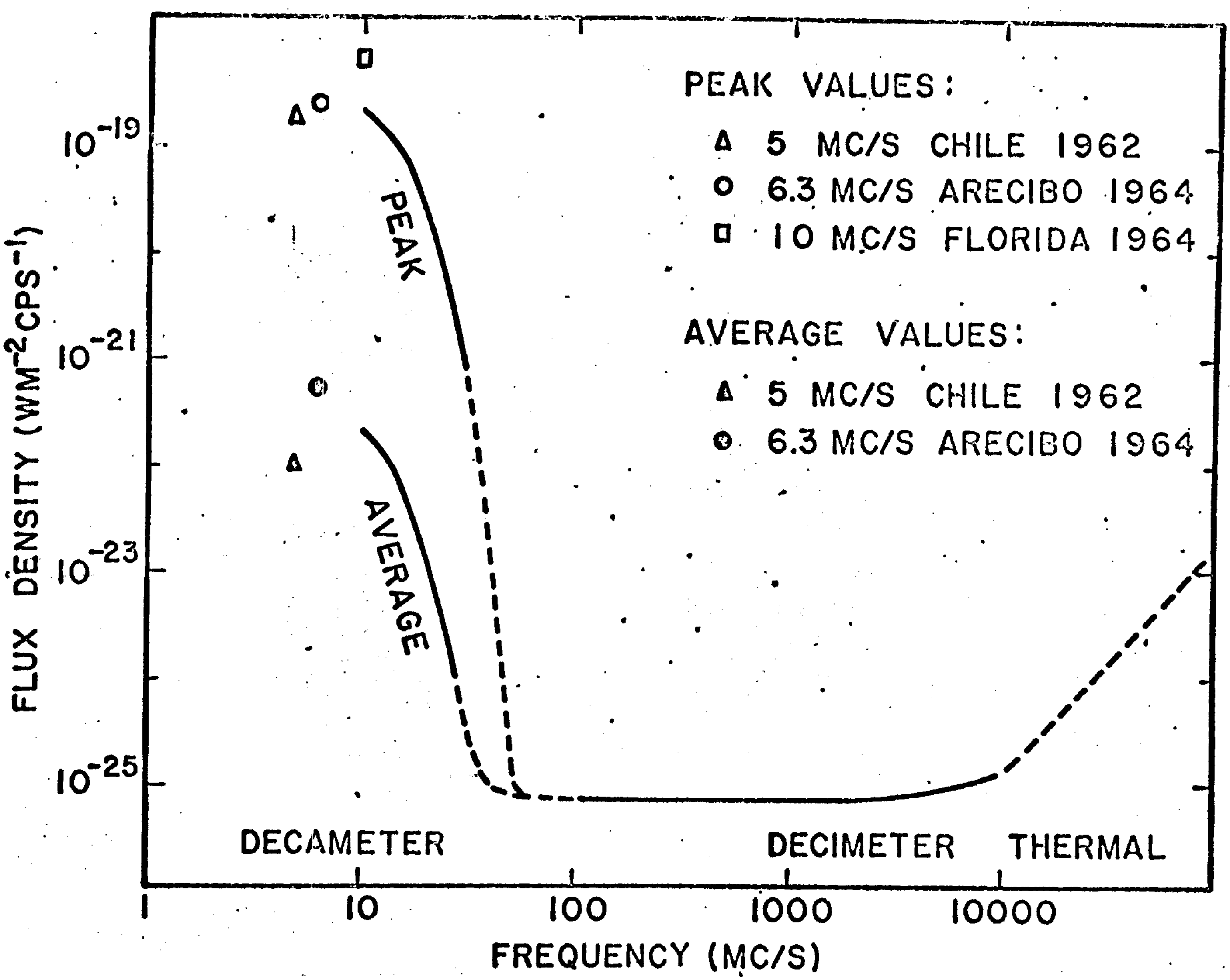
Figure 5. Variation of polarization with longitude at 10 Mc/s. Bar heights indicate standard deviation for a single measurement.

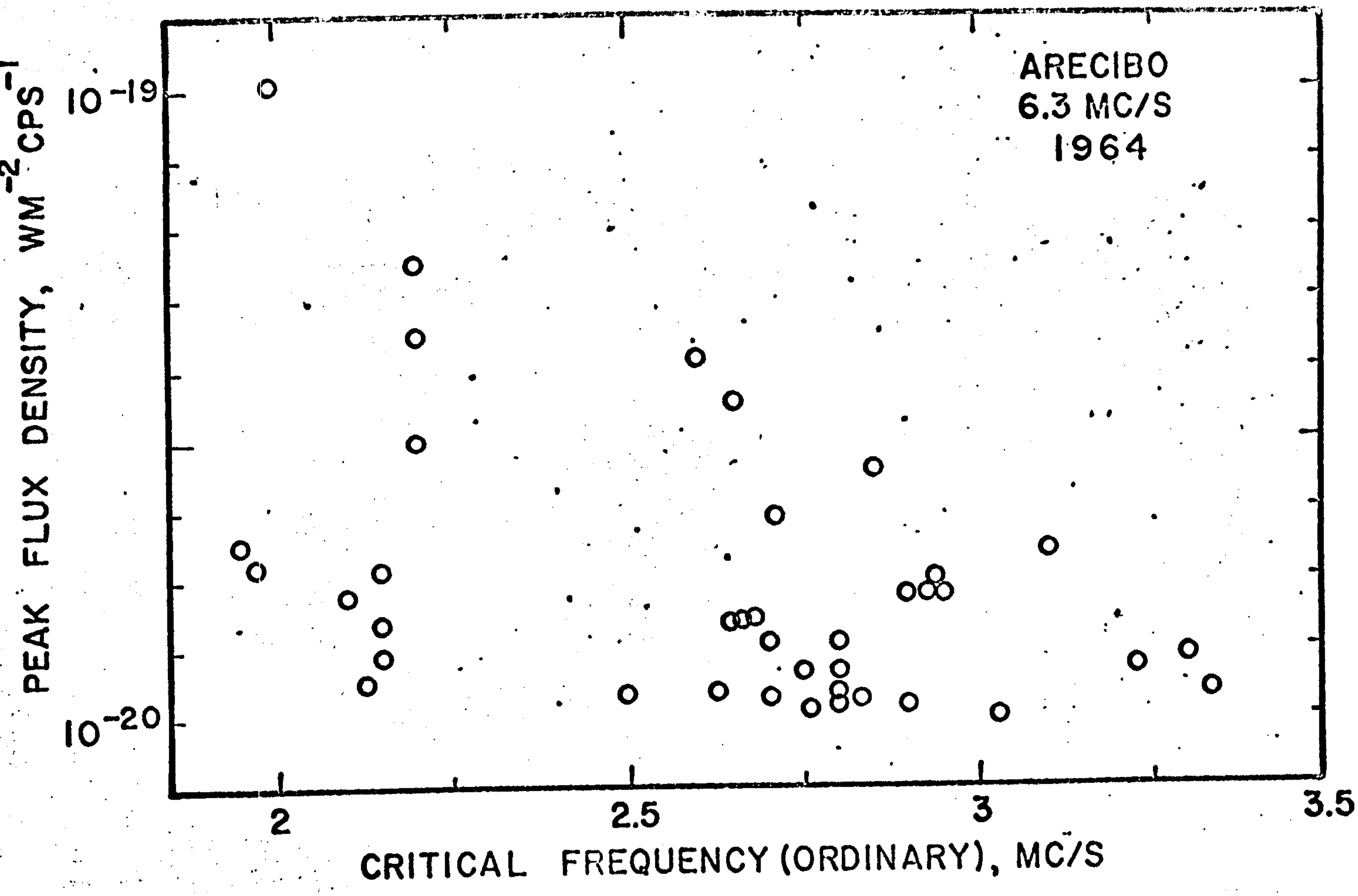
Figure 6. Smoothed curves showing longitude variation of polarization at three frequencies.

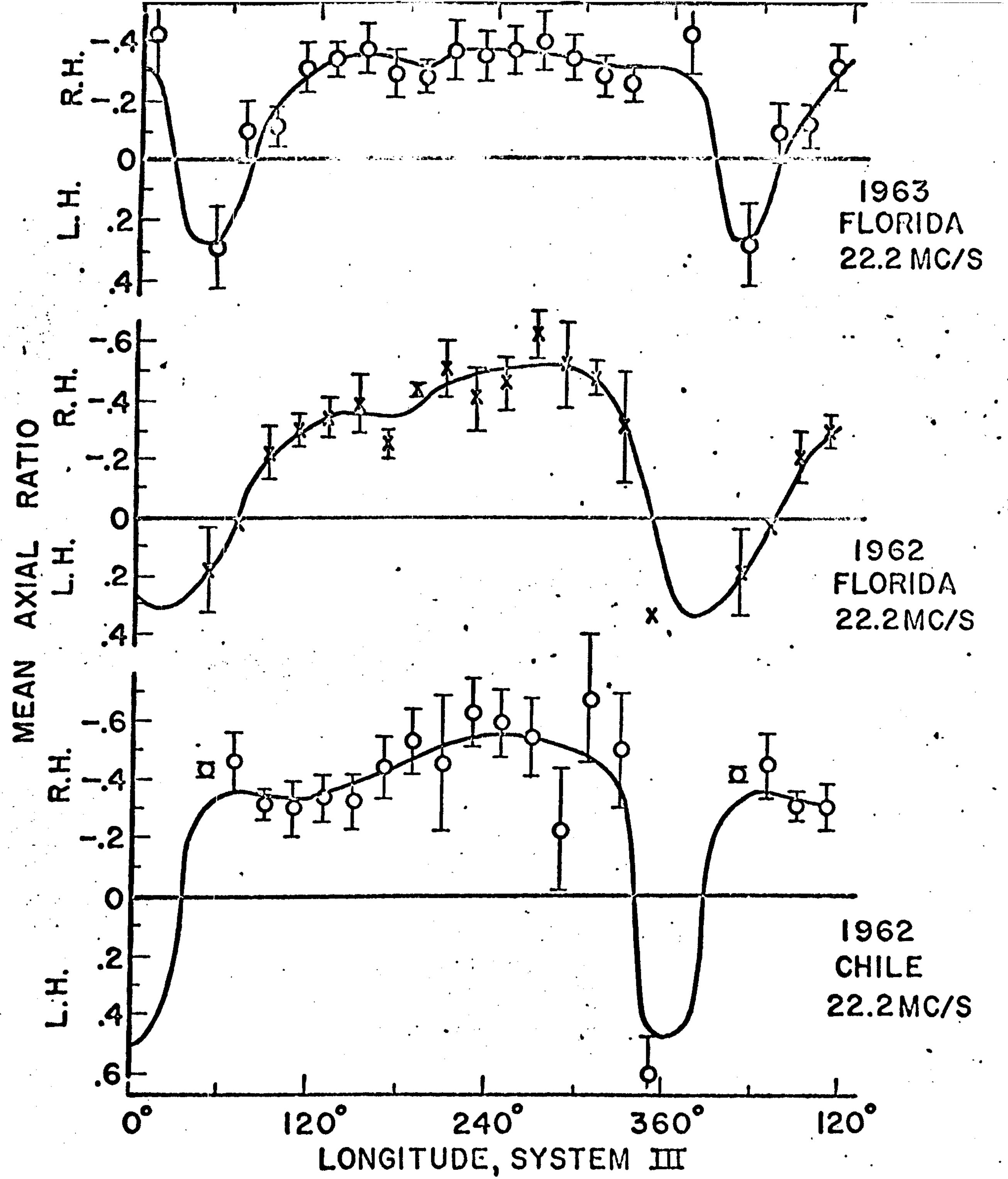
Figure 7. Distributions of axial ratio values.

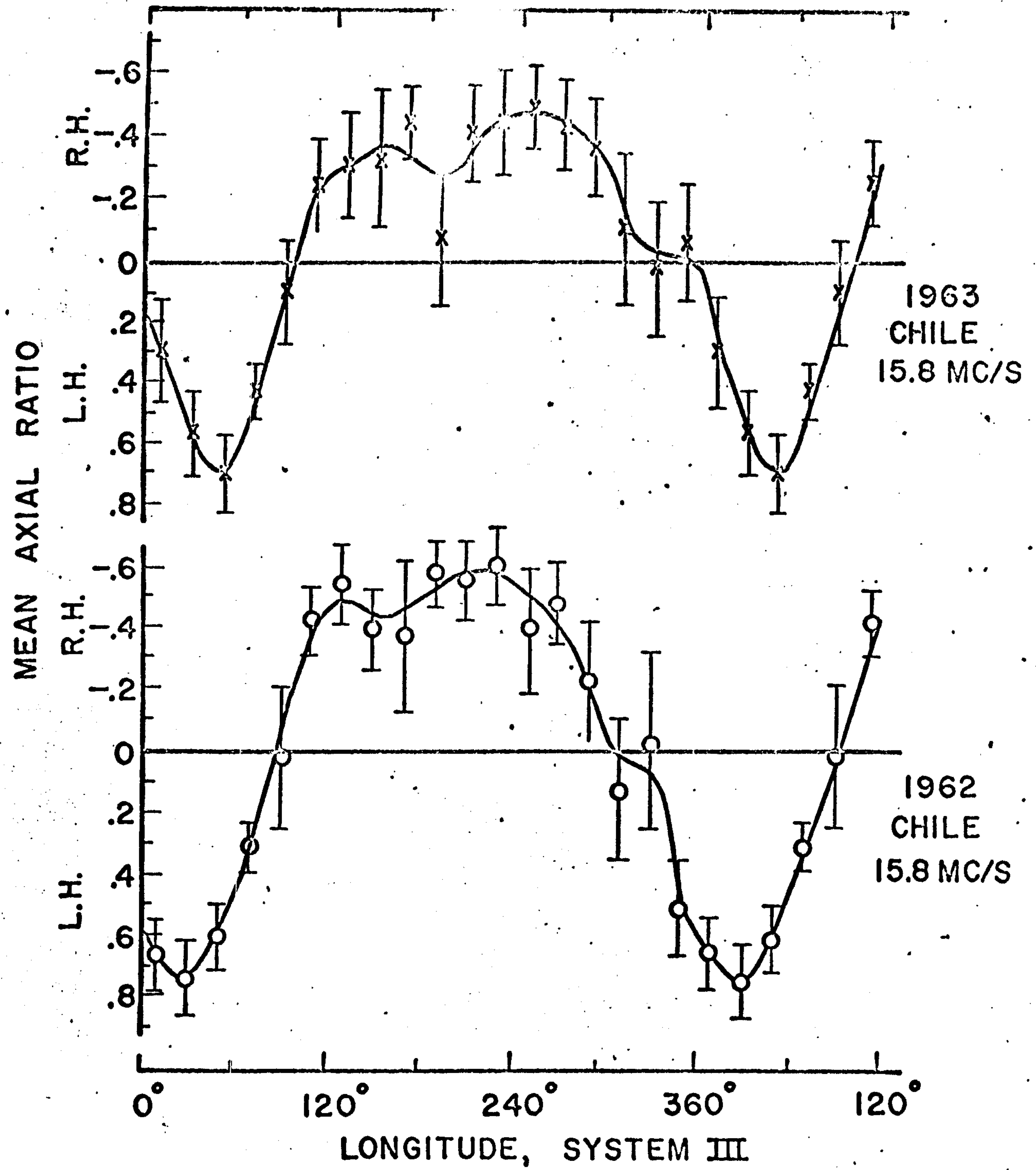
Figure 8. Smoothed curves showing variation of axial ratio and occurrence probability with longitude. Vertical dashed lines indicate assumed longitudes of poles.

Figure 9. Effect of critical frequency upon axial ratio.


PEAK VALUES:
5 MC/S CHILE 1962
6.3 MC/S ARECIBO 1964
10 MC/S FLORIDA 1964
AVERAGE VALUES:
5 MC/S CHILE 1962
6.3 MC/S ARECIBO 1964
PEAK
AVERAGE
DECAMETER
DECIMETER
THERMAL
FLUX DENSITY (WM^{-2}CPS^{-1})
10^{-19}
10^{-21}
10^{-23}
10^{-25}
1
10
100
1000
10000
FREQUENCY (MC/S)

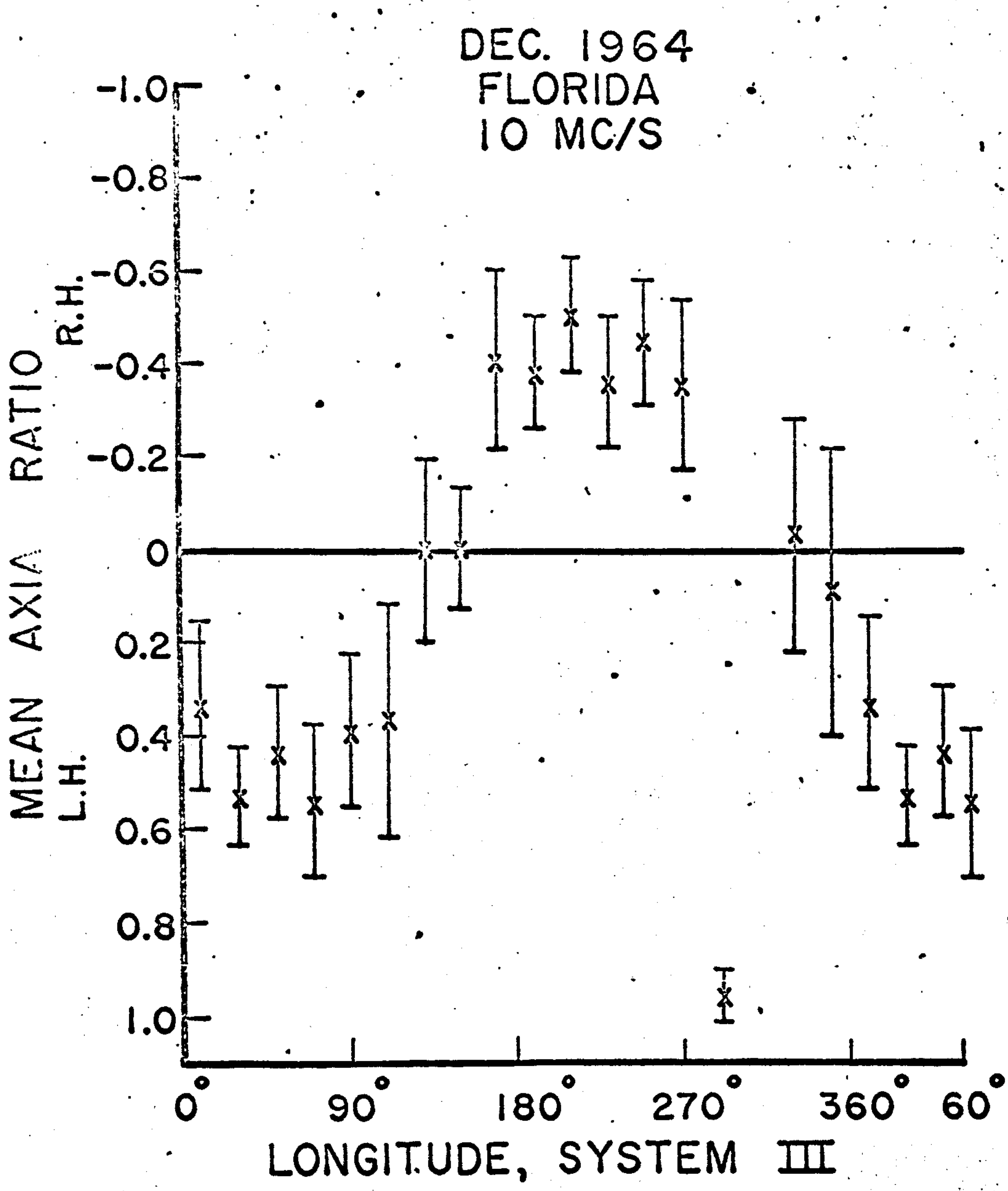

ARECIBO
6.3 MC/S
1964
PEAK FLUX DENSITY, WM^{-2}CPS^{-1}
10^{-19}
10^{-20}
2
2.5
3
3.5
CRITICAL FREQUENCY (ORDINARY), MC/S

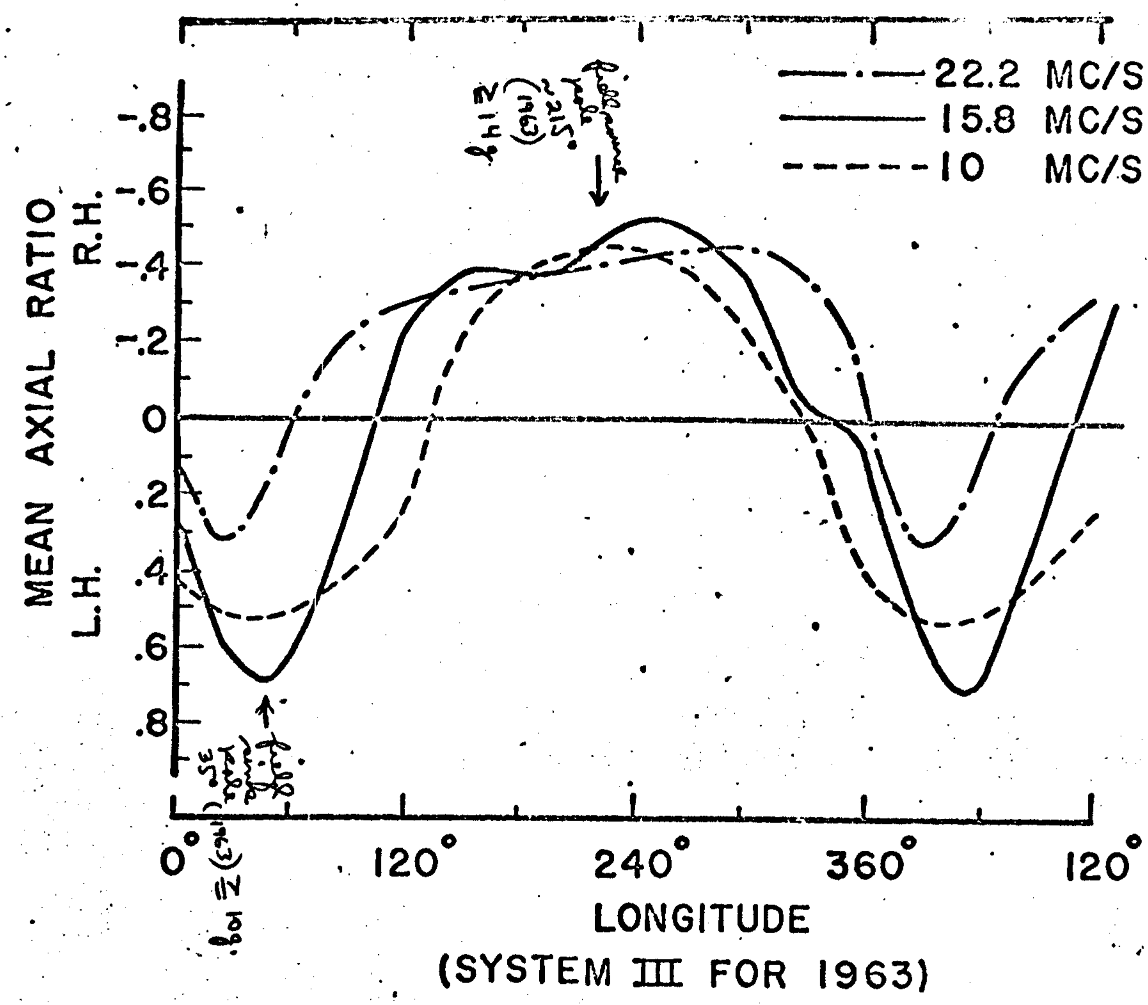

1963
FLORIDA
22.2 MC/S
1962
FLORIDA
22.2MC/S
1962
CHILE
22.2MC/S
R.H.
L.H.
MEAN AXIAL RATIO
-.6
-.4
-.2
0
.2
.4
.6
0°
120°
240°
360°
120°
LONGITUDE, SYSTEM III

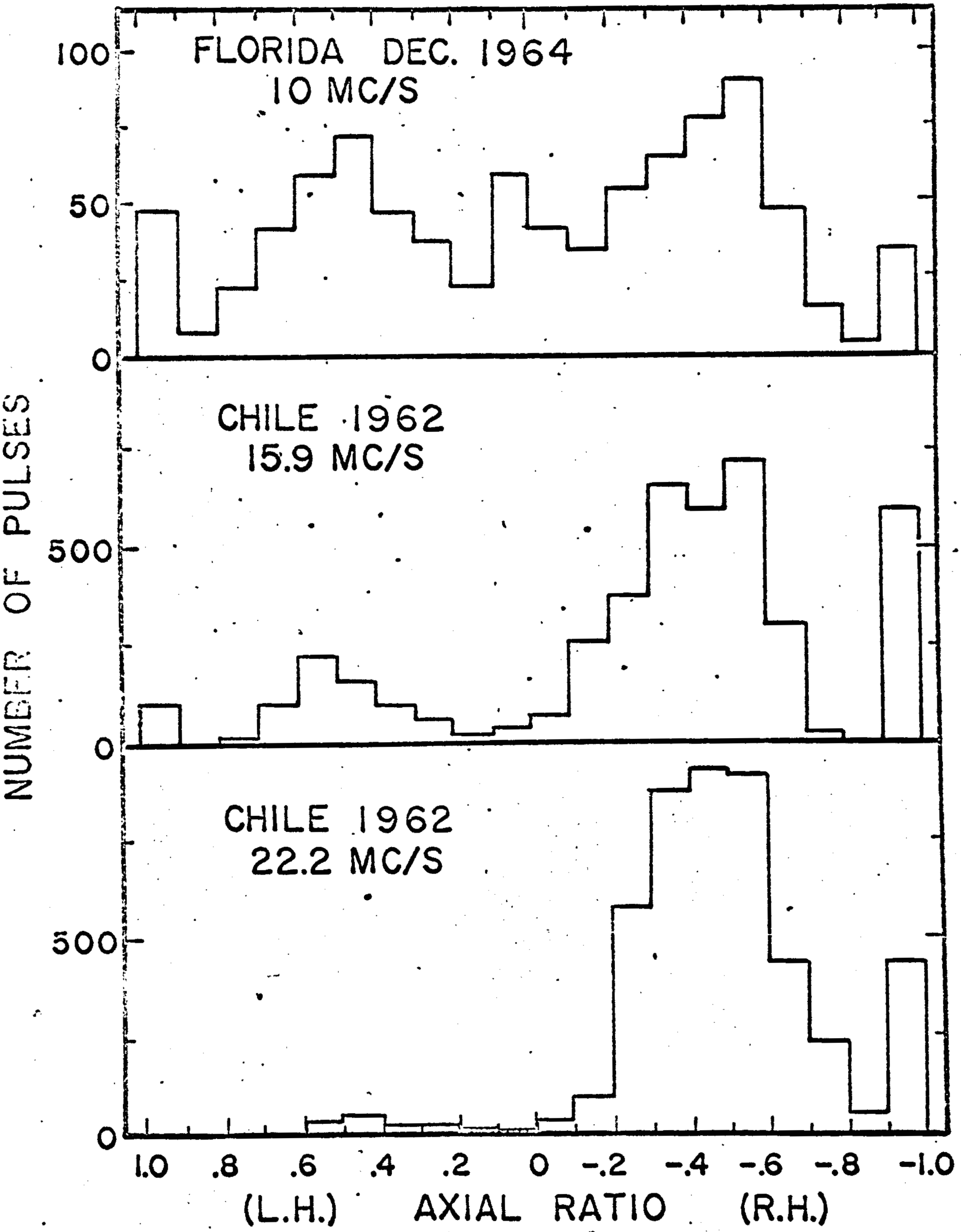

MEAN AXIAL RATIO
R.H.
L.H.
-.6
-.4
-.2
0
.2
.4
.6
.8
1963
CHILE
15.8 MC/S
1962
CHILE
15.8 MC/S
0°
120°
240°
360°
120°
LONGITUDE, SYSTEM III

TCP

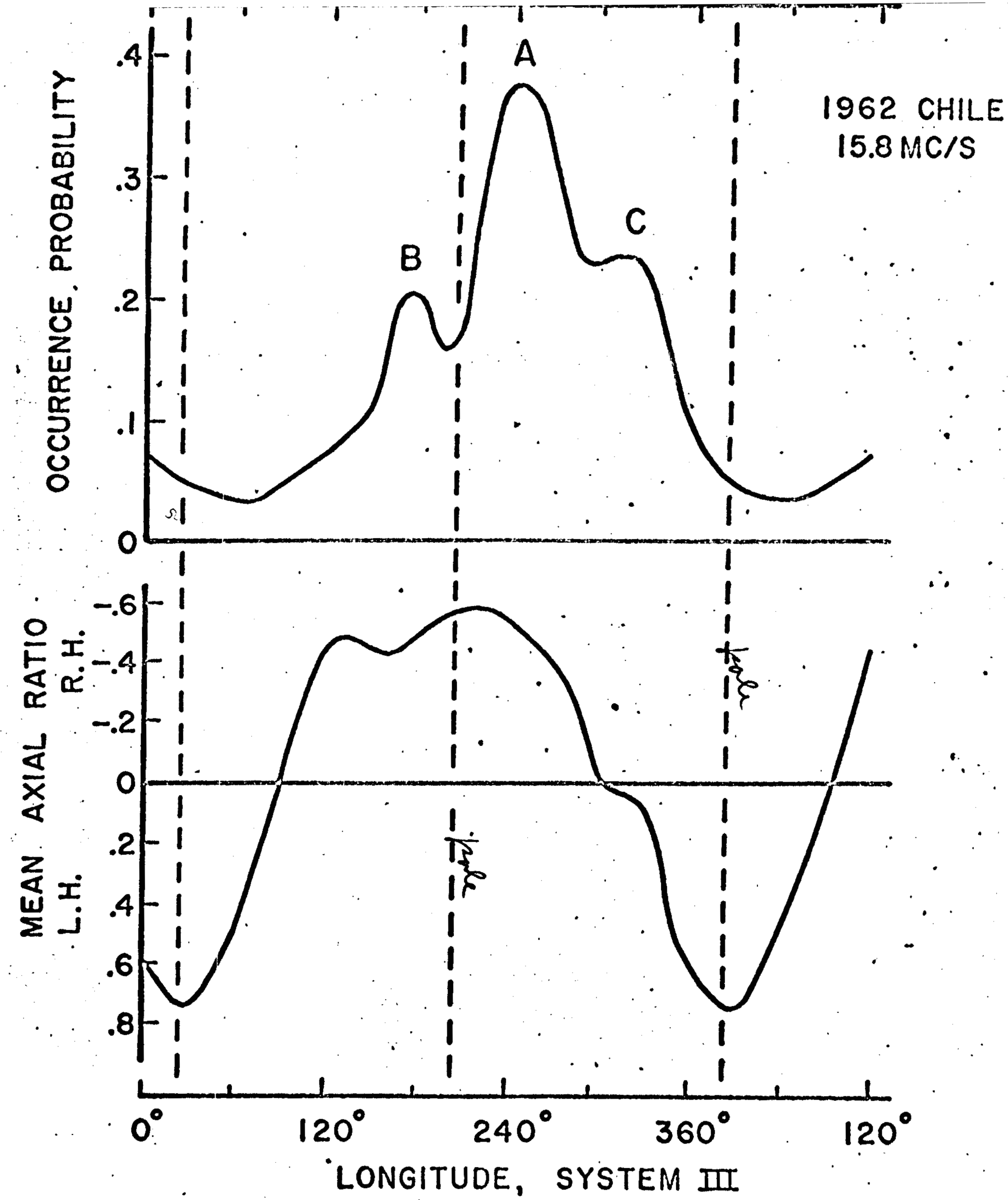
Fig 5


DEC. 1964
FLORIDA
10 MC/S
-1.0
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1.0
R.H.
L.H.
MEAN AXIAL RATIO
0°
90°
180°
270°
360°
60°
LONGITUDE, SYSTEM III

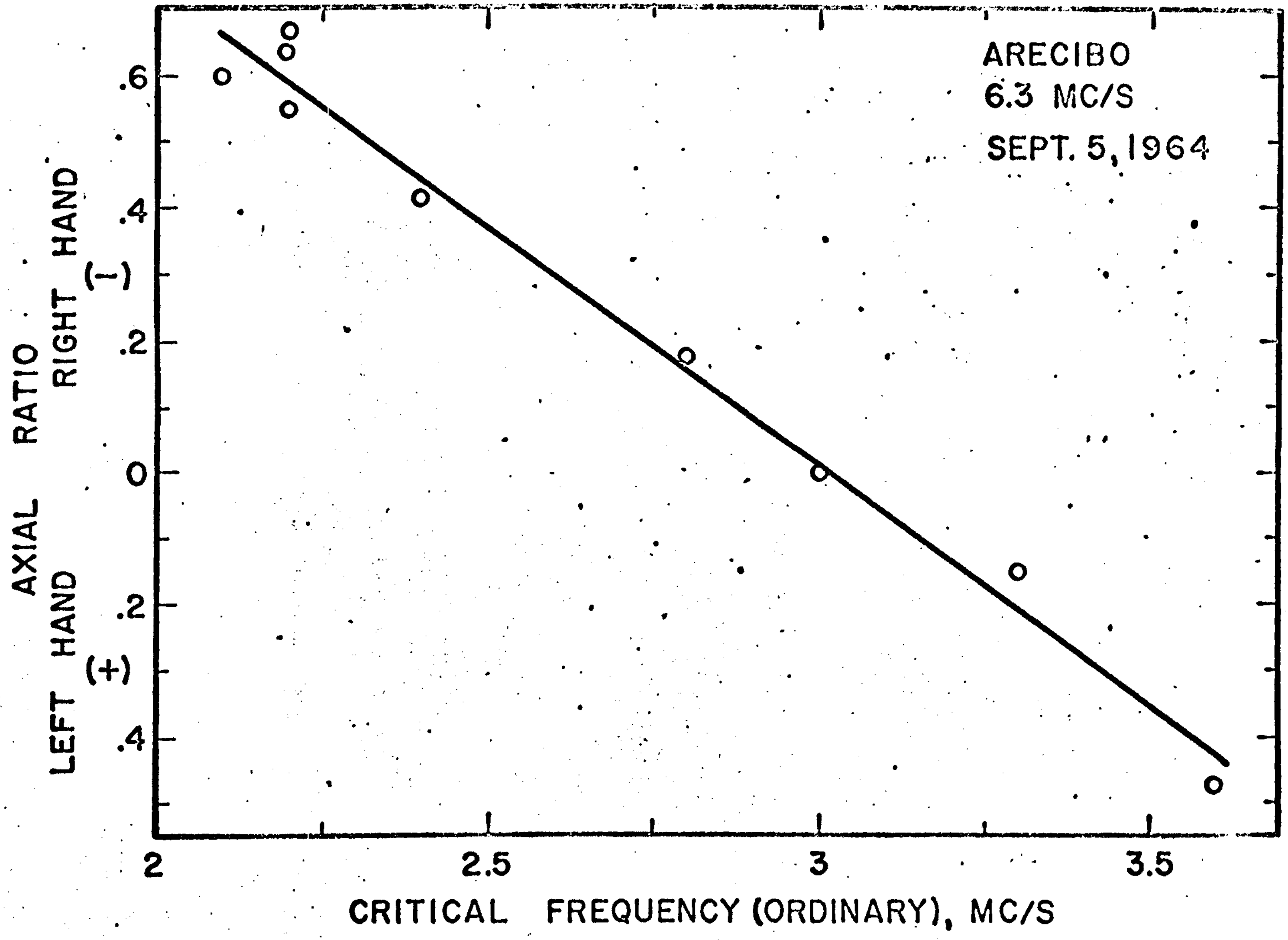

22.2 MC/S
15.8 MC/S
10 MC/S
MEAN AXIAL RATIO
R.H.
L.H.
-.8
-.6
-.4
-.2
0
.2
.4
.6
.8
0°
120°
240°
360°
120°
LONGITUDE
(SYSTEM III FOR 1963)
field source pole ~215° (1963) ≅ 14g
field sink pole 35° (1963) ≅ 10g.



FLORIDA DEC. 1964
10 MC/S
CHILE 1962
15.9 MC/S
CHILE 1962
22.2 MC/S
NUMBER OF PULSES
100
50
0
500
0
500
0
1.0
.8
.6
.4
.2
0
-.2
-.4
-.6
-.8
-1.0
(L.H.)
AXIAL RATIO
(R.H.)



1962 CHILE
15.8 MC/S
A
B
C
OCCURRENCE PROBABILITY
.4
.3
.2
.1
0
MEAN AXIAL RATIO
R.H.
L.H.
-.6
-.4
-.2
0
.2
.4
.6
.8
pole
pole
0°
120°
240°
360°
120°
LONGITUDE, SYSTEM III


ARECIBO
6.3 MC/S
SEPT. 5, 1964
AXIAL RATIO
RIGHT HAND (–)
LEFT HAND (+)
.6
.4
.2
0
.2
.4
2
2.5
3
3.5
CRITICAL FREQUENCY (ORDINARY), MC/S